Evaluation of Enthalpies of Benzene—Monosubstituted Benzene Interactions by Semi-Empirical MO Calculations. Their Relationship to the Experimental Enthalpies Determined by GLPC

Tadashi ENDO[a]*, Takahiro IIDA[a], Nobuhide FURUYA[a],
Yumiko YAMADA[b] and Masato M. ITO[b]

[a]Department of Chemistry, College of Science and Engineering,
Aoyama Gakuin University, Chitosedai, Setagaya-ku, Tokyo 157-8572, Japan
[b]Faculty of Engineering, Soka University
Tangi-cho, Hachioji, Tokyo 192-8577, Japan

(Received: September 21, 1998 ; Accepted for publication: January 18, 1999 ; Published on Web: May 19, 1999)

Enthalpies of benzene—monosubstituted benzene interactions were evaluated by semi-empirical MO calculations of heats of formation for (i) the benzene (PhH) dimer and (ii) benzene—monosubstituted benzene (PhX) pairs. Calculation methods, initial intermolecular distances (r_I), and so on were investigated for the benzene dimer. The interaction enthalpy and optimized geometry calculated with PM3 were consistent with the previous experimental and theoretical results. As initial arrangements of PhH—PhX systems, one parallel (**P**) and four vertical arrangements ($\mathbf{V}_r$, $\mathbf{V}_p$, $\mathbf{V}_m$, and $\mathbf{V}_b$) were chosen (Figure 1). In the case of $\mathbf{V}_p$ or $\mathbf{V}_m$ arrangement where the lowest H atom at the para or meta position to substituent X in PhX was located above the centroid of PhH, calculated enthalpies of the interactions ($\Delta\Delta H_f$) between PhH and PhX had close correlation with experimental ones ($\Delta\Delta H^{\mathrm{t}}$) determined by gas-liquid partition chromatography (GLPC), with the correlation coefficient (ρ) as large as 0.94 (Figure 5); differences between the experimental $\Delta\Delta H^{\mathrm{t}}$ values and the $\Delta\Delta H^{\mathrm{t}}$ values calculated from the correlation equation were less than ca. 0.1 kcal mol^{-1} . With the other arrangements except for $\mathbf{V}_p$, no appreciable relationship was observed between the $\Delta\Delta H_f$ and $\Delta\Delta H^{\mathrm{t}}$ (Figures 2–4).

Keywords: Intermolecular interaction, Aromatic-aromatic interaction, Benzene-monosubstituted benzene, MOPAC93, Relationship between calculated and experimental interaction enthalpies

1 Introduction

Precise molecular recognition is essential to living systems. For example, the following biological discrimination is well known: enzyme-substrate [1], antigen-antibody [2], nucleic acid-protein [3], drug-receptor [4], and hormone-receptor recognition [5]. In contrast, a very large number of studies have recently been made on chemical recognition mainly using various model compounds of host-guest type such as crown ethers [6], criptands [7], calixarenes [8], and convergent cleft molecules [9]. It is now accepted that molecular recognition, whether biological or chemical [10], is due to specific weak (noncovalent) interactions between interacting groups in the respective molecules.

Concerning weak interactions between groups, comparable in energies (or enthalpies) to van der Waals interactions, experimental studies have extensively been made. These include dipole—induced dipole interaction between the 1,3-dioxane and phenyl rings [11], an alkyl—phenyl interaction [12], an alkyl—alkyl interaction [13] including that between two *t*-butyl groups [14], and so on. In addition, recent theoretical studies on aromatic—aromatic interactions suggested an energetically favorable orientation of two aromatic rings as well as their interaction energies [15–17].

We have been studying factors controlling such precise molecular recognition as occurs in living systems, by use of a pair of acylurea derivatives [open chain analogues of pyrimidine bases (e.g., uracil and thymine)] which can associate strongly with each other as well as with themselves [18]. As a result, it has been clarified that (i) intermolecular association is the first requirement for molecular recognition [19], (ii) three-dimensional shape similarity between interacting groups in reacting molecules is responsible for more specific and precise molecular recognition than would otherwise be achieved [20].

These findings led us to investigate weak interactions between interacting groups. Using GLPC, it has been demonstrated that (i) enthalpies of weak interactions of a phenyl group ($\Delta\Delta H^{\mathrm{t}}$)with substituted benzenes [21], alkanes [22], alkenes [23], ethers [23], and carbonyl compounds [21] range from -2.7 to +0.1 kcal mol^{-1} (1 cal = 4.184 J) and (ii) methylation or methoxylation of a benzene ring weakens or strengthens, respectively, the phenyl—phenyl interaction [21]. Further examinations have revealed that degree of the recognition between molecules each having a nonpolar group can be controlled by the strength of shape-specific weak interactions between nonpolar groups in the respective molecules [24].

The above-mentioned experimental enthalpies of the interactions [21] can only be determined with a phenyl group as one component, because of limitation of stationary liquids available in GLPC. Thus, some theoretical approaches to evaluate *weak interactions* between relatively nonpolar molecules will help to elucidate an entire picture of the weak interactions including their shape-specificity. This approach need not be very accurate and quantitative; it should, however, be (i) precise enough to bring about good correlation with experimental results and (ii) convenient enough to make it possible to calculate the interaction energies between the phenyl and a wide variety of groups within a realistic time.

Ab initio calculations seem not to be suitable for this purpose; they require enormous time and resources of the computer because of complicated calculations of configuration interactions (CI) using a large number of basis sets, the calculation methods being still a subject of theoretical chemists even for the intermolecular interaction of a methane dimer [25]. There appear to have been no calculation methods available for electron correlation which enable calculations of interactions between benzene and substituted benzenes to be precise enough within a realistic time. On the other hand, for semi-empirical methods such as PM3 in MOPAC where (i) CI calculations are not implemented explicitly and (ii) the effect corresponding to electron correlation is supposed to be incorporated implicitly in the set of adjustable parameters, the use of which is characteristic of semi-empirical calculations. This is evident from the fact that heats of formation for various organic compounds can be evaluated with considerable accuracy by means of MOPAC [26].

With this situation in mind, MOPAC was used to evaluate enthalpies of intermolecular interactions, and the effectiveness and limitations of the semi-empirical method were examined. In this paper, we wish to report that the calculated enthalpies of weak interactions between benzene and various substituted benzenes have close correlation with the corresponding experimental enthalpies determined by GLPC.

2 Calculation methods

All calculations were carried out with the MOPAC93 program [27] for Power Macintosh (CS MOPAC, Fujitsu Ltd.) on Apple Power Macintosh 7200/120.

As monosubstituted benzenes (PhX), anisole (PhOMe), benzene (PhH), chlorobenzene (PhCl), N,N-dimethylaniline ($PhNMe_2$) , ethylbenzene (PhEt), fluorobenzene (PhF), nitrobenzene ($PhNO_2$) , and toluene (PhMe) were used.

As *initial arrangements* of a pair of benzene and a monosubstituted benzene (PhH—PhX system), one parallel (**P**) and four vertical arrangements ($\mathbf{V}_r$, $\mathbf{V}_p$, $\mathbf{V}_m$, and $\mathbf{V}_b$) were chosen (Figure 1*a*). In **P** arrangement, two benzene rings of PhH and PhX molecules are stacked parallel to each other. In $\mathbf{V}_r$ arrangement, the lowest H atom of PhH points to the center of the benzene ring of PhX. In $\mathbf{V}_p$ (Figure 1*b*) or $\mathbf{V}_m$ arrangement, the lowest H atom at the para or meta position, respectively, to substituent X is located above the centroid of PhH. In $\mathbf{V}_b$ arrangement, substituent X lying at the lowest position ("bottom") of PhX is located above the centroid of PhH.

In the case of **V** arrangements, an *intermolecular distance* is defined as the distance between the centroid of a benzene ring lying on a plane and the lowest atom (H or X) of the other PhH or PhX molecule located above the centroid of the former benzene ring (Figure 1). With **P** arrangement, an intermolecular distance is defined as the distance between the facing "above" and "below" carbon atoms of two benzene rings of parallel orientation.

Setting up of an *initial intermolecular distance* (r_I) was performed using Chem3D (CambridgeSoft Corp.) ver. 3.5 by geometrical calculation so that the r_I may become the desired value (e.g., 2.60, 2.75, 3.05, 3.20, or 3.40 Å). In the case of $\mathbf{V}_b$ arrangement, setting up of the r_I is shown in the caption of Figure 1.

Energy minimization (geometry optimization) was carried out in the following way both for a single molecule (PhH or PhX) and for a pair of molecules (PhH—PhX system), thereby giving their heats of formation (ΔH_f) : (1) in the case of a single molecule, the structure preliminarily optimized by Chem3D was subject to geometry optimization with MOPAC calculation; (2) with a PhH—PhX system, (i) its initial arrangement (Figure 1) was set up, using the optimized structures of a PhH molecule and a single PhX one mentioned above, (ii) the r_I was then set up, and (iii) energy minimization was performed with MOPAC calculation.

In general, *enthalpy of interaction* ($\Delta\Delta H_f$) between A and B molecules can be defined as Eq. 1, where ΔH_f (A—B) is heat of formation of coexisting A and B molecules, ΔH_f (A) is

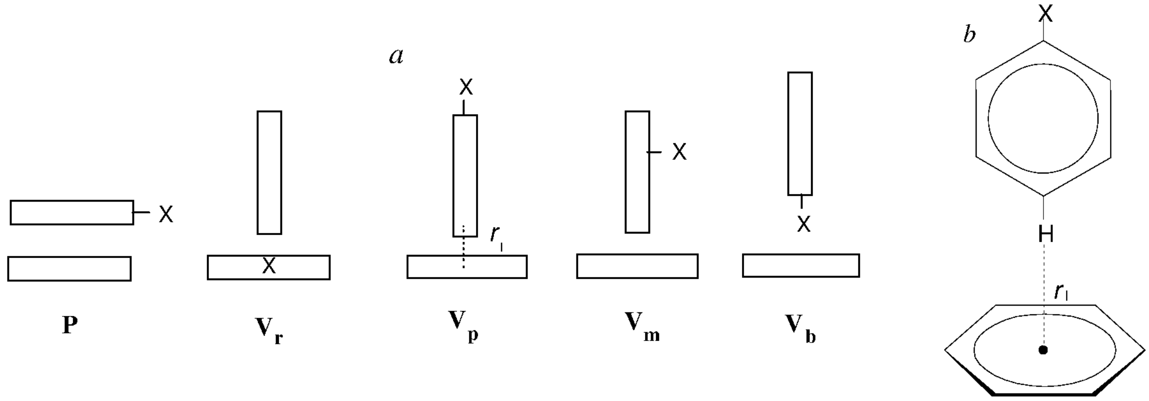

Figure 1. (*a*) Schematic drawings of initial arrangements (**P**, $\mathbf{V}_r$, $\mathbf{V}_p$, $\mathbf{V}_m$, and $\mathbf{V}_b$) of benzene (PhH)—monosubstituted benzene (PhX) systems; (*b*) a drawing of initial arrangement $\mathbf{V}_p$. The symbol r_I represents an initial intermolecular distance; for definition, see the text. The symbol X shows a substituent of benzene. In the case of $\mathbf{V}_b$ arrangement, the r_I for X = Me, Et, MeO, NMe_2, or NO_2 is the distance between the H atom in these groups (except for a NO_2 group [the O atom instead of the H atom]) and the "closest" C atom in PhH; for X = NMe_2 or NO_2, the N atom in these two groups is located above the centroid of PhH. In view of van der Waals radii of Cl (1.80 Å), F (1.35 Å), and O (1.40Å), the r_I values set up for these are 3.50, 3.05, and 3.1 Å, respectively. For the other type of initial arrangement $\mathbf{V}_r$ ($\mathbf{V}_r{}^{\mathbf{R}}$) where a PhH molecule located above a PhX molecule is rotated by 90° relative to PhX, the $\Delta\Delta H_f$ values are also evaluated.

that of A

$$\Delta\Delta H_f = \Delta H_f \text{ (A—B)} - \Delta H_f \text{ (A)} + \Delta H_f \text{ (B)} \qquad (1)$$

molecule, and ΔH_f (B) is that of B molecule.

3 Results and discussion

PhH—PhH Interactions

Evaluation of interaction enthalpies ($\Delta\Delta H_f$) of benzene—benzene interaction for initial arrangement **V** was performed with three methods (MNDO, AM1, and PM3) and the results were compared with one another (Table 1). In view of the fact that (i) a half of thickness of a benzene ring is 1.7 Å and (ii) van der Waals radius of an H atom is 1.2 Å, heats of formation (ΔH_f) were calculated, with structures optimized for various initial intermolecular distances (r_I) of 2.60, 2.75, 3.05, and 3.20 Å. The intermolecular distance (r_o) optimized with PM3 method, for instance, was ca. 2.5 Å, irrespective of the r_I. The corresponding ΔH_fs for initial structure **V** were 46.53 (r_I = 3.20 Å), 46.48 (3.05 Å), 46.35 (2.75 Å), and 46.29 kcal mol^{-1} (2.60 Å), whereas those for the optimized structures were all 46.26 kcal mol^{-1}, regardless of the r_I. It has been clarified that (i) MNDO and AM1 methods tend to overestimate the intermolecular interactions and (ii) PM3 method is most suitable since it gives the $\Delta\Delta H_f$ values close to the *experimental* interaction enthalpy ($\Delta\Delta H^t$) of -1.32 kcal mol^{-1} (X = H) [28].

Table 1. Effect of calculation methods on the $\Delta\Delta H_f$ for initial arrangements **V** and **P** of PhH—PhH system[a]

r_I /Å	$\Delta\Delta H_f$ / kcal mol^{-1}			
	MNDO (**V**)	AM1 (**V**)	PM3 (**P**)	PM3 (**V**)
2.60	-4.29	-2.96	0.06	-0.52
2.75	-4.30	-2.94	0.06	-0.52
3.05	-4.29	-2.95	0.06	-0.52
3.20	-4.29	-2.96	0.06	-0.52

[a] The following key words were chosen for PM3 method. (1) For a PhH or PhX molecule: PM3 EF XYZ PRECISE GNORM = 0.01; (2) for a PhH-PhX system: PM3 EF XYZ PRECISE GNORM = 0.05 LET DDMIN = 0.0.

It is also evident from the data in Table 1 that the $\Delta\Delta H_f$ values by PM3 method for **V** and **P** arrangements (X = H) are -0.52 and 0.06 kcal mol^{-1}, respectively, regardless of the r_I. Since the experimental interaction enthalpy ($\Delta\Delta H^t$) for X = H is -1.32 kcal mol^{-1}, **V** arrangement appears to be more suitable as an initial arrangement of the system than **P** arrangement.

An *optimized intermolecular distance* for the benzene dimer was shown to be 5.0 Å between their centroids (d_{cb-cb}) by ab initio calculations [16, 29], molecular dynamics simulations [30], and Monte Carlo simulations [31]. In the present work, the d_{cb-cb} becomes 4.978 Å [32], the distance practically equal to that obtained by the previous work mentioned above.

Ab initio calculations of the benzene dimer indicated that interplanar angles (dihedral angles) between interacting benzene molecules approaching 90°, the "T-stacked" arrangement, are enthalpically favorable [16]. Moreover, when they adopt edge-to-face stacked orientation [17], electrostatic interaction between two benzene rings is reported to be attractive (-1.4 kcal mol^{-1}). These findings agree with our result that the optimized geometry, which leads to close relationship between the $\Delta\Delta H_f$ and $\Delta\Delta H^t$, is similar to the initial arrangement of vertical type (**V**). The T-shaped orientation of two benzene molecules is well recognized in four kinds of studies: (i) crystal structures of benzene [33], peptides (and proteins) [15], and organic compounds [34], (ii) molecular beam electric deflection studies [35], (iii) NMR studies [36], and (iv) theoretical calculations [30, 31, 37].

As to *interaction energy*, ab initio calculations of the benzene dimer for various orientations [16] revealed that the interaction energy minimum was ca. -2.4 kcal mol^{-1}; a similar result was obtained by more recent calculations that the interaction energy for the T-shaped structure was -2.64 kcal mol^{-1} [29, 38, 39]. Moreover, NMR studies showed the enthalpy (ΔH) of the benzene—benzene interaction to be ca. -2.0 kcal mol^{-1} [40], the ΔH value corresponding to the $\Delta\Delta H^t$ of -1.32 kcal mol^{-1} for X = H; transfer of a benzene molecule from an environment of saturated hydrocarbon molecules into an environment of benzene molecules is energetically favorable to an extent ranging to ca. -l kcal mol^{-1} [41]. These theoretical and experimental results suggest the enthalpy of PhH—PhH interaction to be ca. -l to -2 kcal mol^{-1}. Accordingly, the calculated enthalpy ($\Delta\Delta H_f$) of the PhH—PhH interaction by PM3 method might be more positive by ca. 0.5 kcal mol^{-1} or more.

PhH—PhX Interactions

As mentioned above, the calculated enthalpy ($\Delta\Delta H_f$) of the PhH—PhH interaction was satisfactory in comparison with interaction energies (or enthalpy) obtained with ab initio calculations and with the experiment. Thus, the $\Delta\Delta H_f$ values were further calculated for various PhH—PhX systems in the case of the five initial arrangements. As the r_I, 2.75 Å was chosen, because the *optimized intermolecular distance* (r_o) for X = H has been shown to be all 2.5 Å except for **P** arrangement r_o =5.41Å), regardless of the r_I [42], and because the sum —— (a half of thickness of a benzene ring) + (van der Waals radius of a H atom) —— is 2.9 Å.

Figure 2 depicts a plot of the $\Delta\Delta H_f$ against the $\Delta\Delta H^t$ for initial arrangement **P** (r_I = 2.75 Å). Arrangements after geometry optimization (*optimized geometries*) have been found to resemble the initial arrangement **P**. For most pairs, the PhH—PhX interactions are slightly repulsive. Optimized intermolecular distances (r_o) change from 4.7 to 5.5 Å. There exists no appreciable relationship between the $\Delta\Delta H_f$ and $\Delta\Delta H^t$.

In the case of initial arrangement $\mathbf{V}_r$ (r_I = 2.75 Å), the PhH—PhX interactions are all attractive, ranging in enthalpies markedly from -0.5 to -5.5 kcal mol^{-1}. Optimized geometries resemble initial arrangement $\mathbf{V}_r$ except for (i) an unreasonable vertical arrangement[VP arrangement](X = Me) where two H atoms facing each other (an H atom of the methyl group in PhMe and an H atom in PhH) are penetrated to each other within the van der Waals radius; (ii) an unreasonable arrangement where the two benzene rings are aligned on the same plane ("coplane") in an edge-to-edge manner, with the two closest H atoms in the respective ring being penetrated to each other within the van der Waals radius[CP arrangement](X = Et); (iii) twisted CP —— another CP-like abnormal arrangement where the two benzene rings are twisted perpendicularly to each other[CP* arrangement](X = F). Furthermore, the r_o values alter from 1.7 to 2.5 Å. There is no appreciable relationship between the$\Delta\Delta H_f$ and $\Delta\Delta H^t$, even if the points for the above-mentioned unreasonable arrangements are excluded.

For initial arrangement $\mathbf{V}_b$, the PhH—PhX interactions are repulsive for X = Me, F, and NO_2 , while attractive for the other Xs. Optimized geometries are similar to initial arrangement $\mathbf{V}_b$ except for (i) X = Et (CP* arrangement) and (ii) X = OMe and NMe_2 (arrangements somewhat different from $\mathbf{V}_b$ arrangement). Moreover, the r_o values alter greatly from 1.7 to 5.6 Å. The $\Delta\Delta H_f$ bears no appreciable relationship to the $\Delta\Delta H^t$.

The $\Delta\Delta H_f$ values for initial arrangement $\mathbf{V}_p$ (r_I = 2.75 Å) are listed in Table 2, together with the $\Delta\Delta H^t$ values for reference. It has been clarified that (i) optimized geometries are similar to initial arrangement $\mathbf{V}_p$ regardless of both the r_I and X and (ii) weak interactions between PhH and PhX are all attractive; the r_o values for each system remain almost unaltered with the r_I (ca. 2.4 to 2.5 Å). A close relationship has been found to exist between the $\Delta\Delta H_f$ and $\Delta\Delta H^t$ (Figure 3), the correlation coefficient (ρ) being as large as 0.94.

In the case of initial arrangement $\mathbf{V}_m$ (r_I = 2.75Å), PhH—PhX interactions are also all attractive (Table 2). Optimized geometries are all similar to initial arrangement $\mathbf{V}_m$. Further, the r_o values remain almost unaltered with the systems (ca. 2.5Å). However, the $\Delta\Delta H_f$ appears to have no appreciable relationship to the $\Delta\Delta H^t$ (Figure 4).

The $\Delta\Delta H_f$ for the electron-donating group (OMe or NMe_2) is more negative with $\mathbf{V}_p$ than with $\mathbf{V}_m$, whereas the $\Delta\Delta H_f$ for the NO_2 group is more negative with $\mathbf{V}_m$ than with $\mathbf{V}_p$ (Table 2). Further, the $\mathbf{V}_p$ and $\mathbf{V}_m$ arrangements are interconvertible simply by rotating the upper benzene ring in PhX (Figure 1*b*) around its C_6 axis by 60 degrees. Thus each system would be able to adopt either $\mathbf{V}_p$ or $\mathbf{V}_m$ arrangement, for which the $\Delta\Delta H_f$ value is more negative. On this basis, of the $\Delta\Delta H_f$ values for the two arrangements, the more negative value was selected

Table 2. Initial arrangements $\mathbf{V}^{\mathrm{a}}$, optimized intermolecular distances (r_o), The $\Delta\Delta H_f$ ($r_I = 2.75$ Å), and the $\Delta\Delta H^{\mathrm{t}}$ [21]

PhX	$\mathbf{V}_p$		$\mathbf{V}_m$		
	r_o /Å	$\Delta\Delta H_f$ kcal mol^{-1}	r_o /Å	$\Delta\Delta H_f$ kcal mol^{-1}	$\Delta\Delta H^{\mathrm{t}}$ kcal mol^{-1}
PhEt	2.51	-0.49	2.51	-0.50	-1.09
PhMe	2.51	-0.50	2.51	-0.50	-1.18
PhF	2.48	-0.64	2.48	-0.67	-1.26
PhCl	2.49	-0.61	2.48	-0.63	-1.29
PhH	2.50	-0.52	2.50	-0.52	-1.32
PhOMe	2.45	-0.80	2.50	-0.53	-1.51
$PhNMe_2$	2.43	-0.80	2.51	-0.48	-1.58
$PhNO_2$	2.45	-0.91	2.54	-1.24	-1.84

[a] In the case of $\mathbf{V}_p$ arrangement, differences in the r_o between the r_I values of 2.75 and 3.05 Å are all within 0.01 Å, and differences in the $\Delta\Delta H_f$ between the r_I values of 2.75 and 3.05 Å are all within 0.01 kcal mol^{-1}.

for each system and plotted against the $\Delta\Delta H^{\mathrm{t}}$ values (Figure 5). A close relationship has also proved to exist between the $\Delta\Delta H_f$ and $\Delta\Delta H^{\mathrm{t}}$, with the ρ being 0.94. In addition, the differences between the experimental $\Delta\Delta H^{\mathrm{t}}$ values and the "$\Delta\Delta H^{\mathrm{t}}$" values calculated from the equation shown in Figure 5 have turned out to be ca. 0.1 kcal mol^{-1} or smaller.

The results described here demonstrate that it is the initial arrangement $\mathbf{V}_p$ or $\mathbf{V}_m$ that brings about close relationship between the theoretical interaction enthalpies ($\Delta\Delta H_f$) and the experimental ones ($\Delta\Delta H^{\mathrm{t}}$).

4 Conclusion

The present work has clarified that enthalpies of weak interactions between benzene (PhH) and monosubstituted benzenes (PhX) can be evaluated by MOPAC93 semi-empirical MO method, the calculated enthalpies having close relationship to the experimental ones, when (i) PM3 method is used as a calculation method and (ii) the initial arrangement of the PhH—PhX system is of the vertical type, in which the lowest H atom at the para or meta position to X in PhX is located above the centroid of PhH. Further, for X = H , the optimized intermolecular distance and optimized geometry [43] are consistent with those obtained with the ab initio calculations.

Evaluation of intermolecular interactions by means of ab initio MO method requires incorporation of electron correlation, for which calculations of considerably large configuration interactions (CI) are necessary. On the other hand, in the case of MOPAC methods such as PM3, it would not be unreasonable to consider that the $\Delta\Delta H_f$ (a measure of weak intermolecular interactions), essentially the difference between the ΔHs (heats of formation), is expected to be evaluated nearly as precisely as the ΔH themselves.

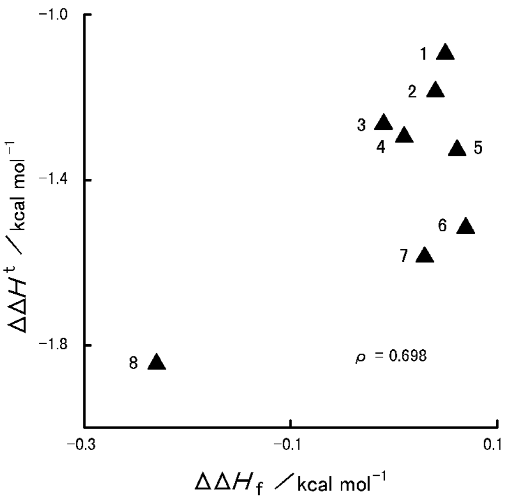

Figure 2. A plot of the $\Delta\Delta H_f$ optimized from initial arrangement **P** (r_I = 2.75 Å) against the $\Delta\Delta H^{\mathrm{t}}$. The numbers show substituents X of PhX: 1, ethyl; 2, methyl; 3, fluoro; 4, chloro; 5, H; 6, methoxy; 7, dimethylamino; 8, nitro group. All optimized geometries are similar to **P** arrangement (▲). In the case of r_I = 3.40 Å, (1) the $\Delta\Delta H_f$ values are equal to those for r_I = 2.75 Å except for (i) X = NMe_2 (more positive by 0.07 kcal mol^{-1}) and (ii) X = Et (more negative by 2.07 kcal mol^{-1}) and (2) optimized geometries are similar to **P** arrangement except for X = Et (an arrangement similar to $\mathbf{V}_r$).

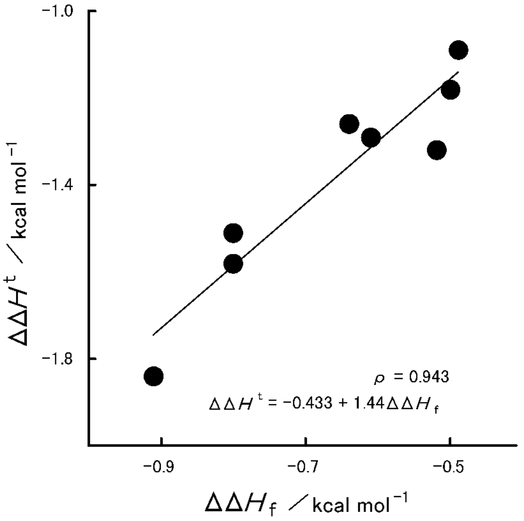

Figure 3. A plot of the $\Delta\Delta H_f$ optimized from initial arrangement $\mathbf{V}_p$ (r_I = 2.75 Å) against the $\Delta\Delta H^{\mathrm{t}}$. PhX molecules used are as in Figure 2. Optimized geometries are similar to $\mathbf{V}_p$ arrangement (●) except for X = MeO and NMe_2 (arrangements somewhat different from $\mathbf{V}_p$).

This is the first example in which theoretical enthalpies of the weak interactions between various pairs of aromatic molecules bear close correlation with the experimental enthalpies. The results presented here encourage us to evaluate enthalpies of weak interactions between benzene and a variety of molecules such as other substituted benzenes and alkenes by semi-empirical MO methods.

We thank Mr. Mitsuru Koike for valuable assistance.

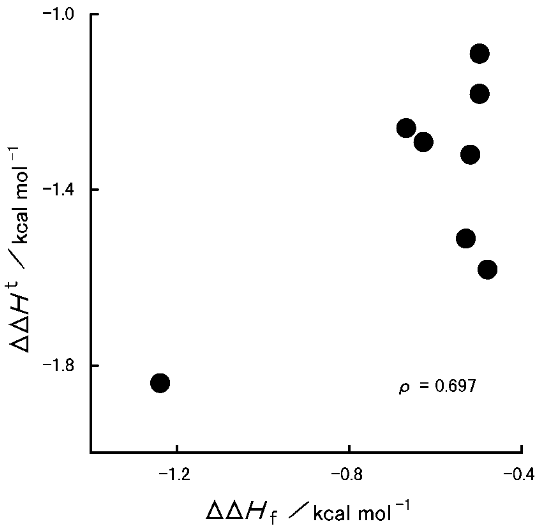

Figure 4. A plot of the $\Delta\Delta H_f$ optimized from initial arrangement $\mathbf{V}_m$ (r_I = 2.75 Å) against the $\Delta\Delta H^{\mathrm{t}}$. PhX molecules used are as in Figure 2. All optimized geometries are similar to $\mathbf{V}_m$ arrangement.

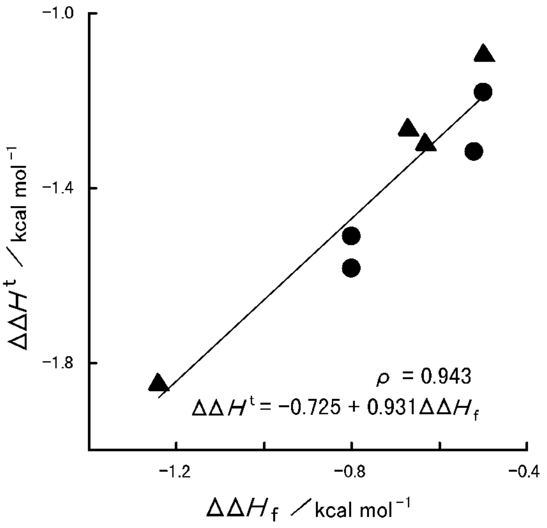

Figure 5. A plot of the $\Delta\Delta H_f$ optimized from initial arrangement $\mathbf{V}_m$ or $\mathbf{V}_p$ (r_I = 2.75 Å) against the $\Delta\Delta H^{\mathrm{t}}$. PhX molecules used are as in Figure 2. The $\Delta\Delta H_f$ values are taken from that for either $\mathbf{V}_m$ or $\mathbf{V}_p$ arrangement: ●, from $\mathbf{V}_p$; ▲, from $\mathbf{V}_m$.

References

[1] Holler, E., *Angew. Chem. Int. Ed. Engl.*, **17**, 648 (1978).
Dixon, M., Webb, E. C., Thorne, C. J. R. and Tipton, K. F., *Enzymes, (3rd. ed.)*, Longman, London (1979), chap. VI.
Cramer, F. and Freist, W., *Acc. Chem. Res.*, **20**, 79 (1987).

[2] Capra, J. D. and Edmundson, A. B., *Sci. American*, **236**, Jan. 50 (1977).

[3] Smith, H. O., *Science*, **205**, 455 (1979).
McKnight, S. L., *Sci. American*, Apr. 32 (1991).

[4] Ariëns, E. J., *Drug Design (Vol. I)*, Ed. by Ariëns, E. J., Academic Press, New York (1971), chap. 1.

[5] Lübke, K., Schillinger, E. and Töpert, M., *Angew. Chem. Int. Ed. Engl.*, **15**, 741 (1976).

[6] Cram, D. J., *Angew. Chem. Int. Ed. Engl.*, **27**, 1009 (1988).

[7] Lehn, J.-M., *Angew. Chem. Int. Ed. Engl.*, **27**, 89 (1988).

[8] Böhmer, V., *Angew. Chem. Int. Ed. Engl.*, **34**, 713 (1995).

[9] Rebek, J., Jr., *Angew. Chem. Int. Ed. Engl.*, **29**, 245 (1990).

[10] Schneider, H.-J., *Angew. Chem. Int. Ed. Engl.*, **30**, 1417 (1991).

[11] Stoddart, J. F., *Chem. Soc. Rev.*, **8**, 85 (1979) and references cited therein.

[12] Watson, A. E. P., McLure, I. A., Bennett, J. E. and Benson, G. C., *J. Phys. Chem.*, **69**, 2753 (1965).
Zushi, S., Kodama, Y., Fukuda, Y., Nishihata, K. , Nishio, M., Hirota, M. and Uzawa, J., *Bull. Chem. Soc. Jpn.*, **54**, 2113 (1981).
Hiraki, Y. and Tai, *Chem. Lett.*, **1982**, 341.

[13] Berg, U., Liljefors, T., Roussel, C. and Sandström, J., *Acc. Chem. Res.*, **18**, 80 (1985).

[14] Lyttle, M. H., Streitwieser, A., Jr. and Kluttz, R. Q., *J. Am. Chem. Soc.*, **103**, 3232 (1981).
Carter, R. E. and Stilbs, P., *J. Am. Chem. Soc.*, **98**, 7515 (1976).

[15] Burley, S. K. and Petsko, G. A., *Science*, **229**, 23 (1985).

[16] Burley, S. K. and Petsko, G. A., *J. Am. Chem. Soc.*, **108**, 7995 (1986).

[17] Hunter, C. A., *Chem. Soc. Rev.*, **1994**, 101 and references cited therein.

[18] Endo, T., *Top. Curr. Chem.*, **128**, 91 (1985).

[19] Endo, T., Kuwahara, A., Tasai, H., Murata, T., Hashimoto, M. and Ishigami, T., *Nature*, **268**, 74 (1977).

[20] Endo, T., Tasai, H., Miyazawa, K., Endo, M., Kato, K., Uchida, A., Ohashi, Y. and Sasada, Y., *J. Chem. Soc., Chem. Commun.*, **1983**, 636.

[21] Ito, M. M., Kato, J., Takagi, S., Nakashiro, E., Sato, T., Yamada, Y., Saito, H., Namiki, T., Takamura, I., Wakatsuki, K., Suzuki, T. and Endo, T., *J. Am. Chem. Soc.*, **110**, 5147 (1988).

[22] Endo, T., Ito, M. M., Yamada, Y., Saito, H., Miyazawa, K. and Nishio, M., *J. Chem. Soc., Chem. Commun.*, **1983**, 1430.

[23] Endo, T., Ito, M. M. and Namiki, T., *J. Chem. Soc., Chem. Commun.*, **1985**, 933.

[24] Endo, T., Tajima, K., Yamashita, M., Ito, M. M., Nishida, J. and Ogikubo, T., *J. Chem. Soc., Chem. Commun.*, **1986**, 1561.

[25] Tsuzuki, S., Uchimaru, T. and Tanabe, K., *Chem. Phys. Lett.*, **287**, 202 (1998).

[26] Kihara, H., Uchida, N. and Ikuta, S., *Bunshi Kido Ho (Molecular Orbital Method)*, Ed. by Osawa, E, Kodansha, Tokyo (1994), p62.

[27] Stewart, J. J. P., *MOPAC93, Revision 2*, Fujitsu Ltd., Nakase, Chiba, 261, Japan (1994).

[28] The $\Delta\Delta H^{\mathrm{t}}$ is the enthalpy of the weak interaction of a PhX molecule with the phenyl group in the stationary liquid (practically PhH molecule) relative to the enthalpy of that of a *n*-octane molecule with the phenyl group.

[29] Hobza, P., Selzle, H. L. and Schlag, E. W., *J. Phys. Chem.*, **97**, 3937 (1993).

[30] Linse, P., *J. Am. Chem. Soc.*, **115**, 8793 (1993).

[31] Jorgensen, W. L. and Severance, D. L., *J. Am. Chem. Soc.*, **112**, 4768 (1990).

[32] $d_{cb-cb} = 2.50\ (r_o) + 1.086$ (C-H bond length of PhH) + 1.392 (C-C bond length of PhX) $= 4.978$ Å

[33] Cox, E. G., Cruickshank, D. W. J. and Smith, J. A. S., *Proc. R. Soc. London A*, **A247**, 1 (1958).

[34] Slawin, A. M. Z., Spencer, N., Stoddart, J. F. and Williams, D. J., *J. Chem. Soc., Chem. Commun.*, **1987**, 1070.

[35] Steed, J. M., Dixon, T. A. and Klemperer, W., *J. Chem. Phys.*, **70**, 4940 (1979).

[36] Laatikainen, R., Ratilainen, J., Sebastian, R. and Santa, H., *J. Am. Chem. Soc.*, **117**, 11006 (1995).

[37] Price, S. L. and Stone, A. J., *J. Chem. Phys.*, **86**, 2859 (1987).
Chipot, C., Jaffe, R., Maigret, B., Pearlman, D. A. and Kollman, P. A., *J. Am. Chem. Soc.*, **118**, 11217 (1996).

[38] An ab inito study [29] of interaction energies of the benzene dimer, however, showed that the parallel-displaced structure is slightly more stable than the above-mentioned T-shaped one by 0.88 kcal mol^{-1}. Similarly, a favorable offset face-to-face π-stacked geometry is predicted using a simple model of the charge distribution in a π-system [Hunter, C. A. and Sanders, J. K. M., *J. Am. Chem. Soc.*, **112**, 5525 (1990)].

[39] It has been suggested that the interaction energy for the benzene dimer calculated with ab initio method depends significantly upon the basis set implemented and the method for electron correlation calculation applied [Hobza, P., Selzle, H. L. and Schlag, E. W., *J. Phys. Chem.*, **100**, 18790 (1996)].

[40] Slejko, F. L., Drago, R. S. and Brown, D. G., *J. Am. Chem. Soc.*, **94**, 9210 (1972).

[41] Jencks, W. P., *Catalysis in Chemistry and Enzymology*, McGraw-Hill, New York (1969), p415.

[42] Optimized intermolecular distances (r_o) are somewhat shorter than the sum of a half of thickness of a benzene ring and van der Waals radius of an H atom. This might be because the H atom in PhX is located just above the centroid of the other benzene ring.

[43] The PM3 MOPAC calculations have revealed that PhH—PhX pairs sometimes adopt irrational structures (e.g., CP and CP*) in which a pair of closest H atoms in the interacting benzene rings are located within the van der Waals spheres. It should be noted that these unreasonable structures are occasionally more "stable", namely, have apparently more negative heats of formation than the realistic ones. Thus, when optimized geometries and/or energetics are studied using the MOPAC program for intra- or intermolecular systems composed of two (or more) aromatic rings, one had better examine whether a non-realistic structure having such an irrationally close contact of the rings is "stabilized" or not.

半経験的分子軌道法によるベンゼン—一置換ベンゼン間相互作用のエンタルピーの計算．ＧＬＰＣで求めた実験値との関係

遠藤 忠[a*], 飯田 貴広[a], 古谷 暢英[a], 山田 由美子[b], 伊藤 眞人[b]

[a] 青山学院大学理工学部化学科　〒157-8572　東京都世田谷区千歳台 6-16-1
*TEL 03-5384-1111, FAX 03-5384-6200
[b] 創価大学工学部生物工学科　〒192-8577　東京都八王子市丹木町 1-236

半経験的分子軌道法を用いて、ベンゼン２量体およびベンゼン（PhH）—モノ置換ベンゼン（PhX）対の生成熱を計算することにより、ベンゼン—モノ置換ベンゼン間相互作用のエンタルピーを求めた。ベンゼン２量体の場合について、計算法、初期の分子間距離（r_I）などを検討した。PM3 法で求めた相互作用エンタルピーと最適化後の配置は、これまでの実験値および計算値と矛盾しない。PhH—PhX 系の初期配置としては、１ケの平行（$\mathbf{P}$）と４ケの垂直配置（$\mathbf{V}_r$ 、$\mathbf{V}_p$ 、$\mathbf{V}_m$ および$\mathbf{V}_b$）（Figure 1）を選んだ。$\mathbf{V}_p$ あるいは$\mathbf{V}_m$ 配置の場合には（この配置では、PhX の置換基 X に対してパラあるいはメタ位にある H 原子が PhH 分子の重心の真上に存在する）、計算から求めた PhH—PhX 間相互作用エンタルピー（$\Delta\Delta H_f$）は、GLPC から求めた実験値（$\Delta\Delta H^{\mathrm{t}}$）と良い相関関係を示し（Figure 5）、相関係数（ρ）は 0.94（$r_I = 2.75$ Å）になった。この相関式から求めた $\Delta\Delta H^{\mathrm{t}}$ と実験値 $\Delta\Delta H^{\mathrm{t}}$ との差は、約 0.1 kcal mol^{-1} 以下であった。他の配置の場合には（$\mathbf{V}_p$ 配置を除くと）、$\Delta\Delta H_f$ と $\Delta\Delta H^{\mathrm{t}}$ との間に相関関係は認められなかった。

キーワード： Intermolecular interaction, Aromatic-aromatic interaction, Benzene-monosubstituted benzene, MOPAC93, Relationship between calculated and experimental interaction enthalpies